5 Observations on Non-residential Property Protection

This section presents the BPAT's observations on non-residential property protection. The non-residential buildings were categorized into the various engineered types of construction focusing on the structural performance of each type of building. Important observations were also made concerning exterior architectural systems (e.g., roof and wall coverings, windows and doors).

A number of non-residential buildings, such as schools, factories, warehouses, and commercial buildings were in the direct path of the tornado vortexes or in the inflow/outflow and received damage. In a few cases, damage could be considered non-structural because architectural and decorative materials on the exterior and roofing were the only damage to the buildings; in engineering standards such as ASCE 7, these materials are often referred to as components and cladding. In other cases, structural damage occurred due to the lack of redundancy in the structural system in the form of a continuous load path to resist wind-induced uplift loads.

5.1 CONTINUOUS LOAD PATH

A continuous load path from the roof structure to a building foundation is essential for a building. This load path, the members and connections between members, is capable of withstanding gravity or downward design loads. However, during high wind events such as tornadoes, lateral loads and uplift loads will act on the building and test the capacity of the continuous load paths. Figure 5-1 shows critical connections in the continuous load paths for representative types of non-residential buildings that sustained structural damage. In addition to the lateral wind forces that are often considered in design, significant uplift loads generated by the high wind velocity associated with tornadoes act on the roofs. To resist these loads, adequate connections must be provided between the roof decking and roof structural support, bar joists or other structural roofing members and walls, and foundation and walls or structural columns. Each of these connections must be capable of resisting uplift and lateral loads as well as gravity loads.

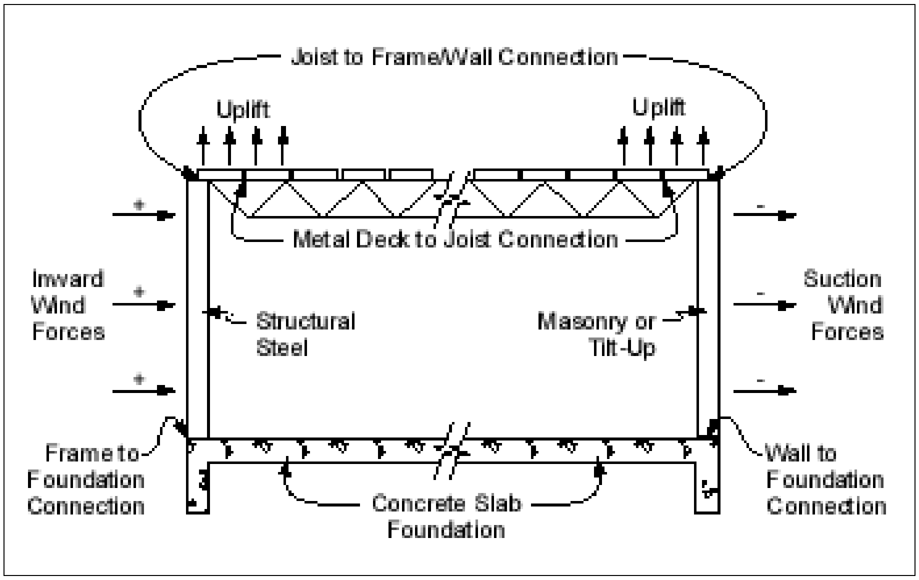


FIGURE 5-1: Critical connections that failed in the load path resulting in structural damage or collapse.

5.1.1 Tilt-up Precast Concrete Walls with Steel Joists

Inspection of a damaged tilt-up precast concrete wall building in Moore, Oklahoma, found no deficiencies with connections between the tilt-up walls and the foundation. However, connections between the roof systems and the tilt-up walls failed in some buildings. In a commercial building along Interstate I-35 outside Del City, Oklahoma, failure of these connections caused a loss of diaphragm action, which then led to collapse of the endwalls of this building and will be discussed further in Section 5.2.1. Figure 5-2 is a photograph of this building. The vortex of a violent tornado passed approximately 200 yards from this building, generating inflow winds that removed the roof of this structure. Once the roof of the building was removed and diaphragm action was lost, the endwall that was already being acted upon by outward (suction) wind forces failed.

FIGURE 5-2: Tilt-up precast concrete walls at a storage building located outside Del City, Oklahoma. After the roof joists separated from the walls, this end wall became unable to withstand suction forces and failed.

5.1.2 Load Bearing Masonry with Steel Joists

The BPAT inspected Kelly Elementary School in Moore, Oklahoma, which was in the direct path of the vortex of the violent tornado. The school included a steel frame building in the main section, and a section that was constructed with load bearing masonry walls with steel joists.

This section discusses the damage associated with the masonry wall section of the building; Section 5.1.3 will discuss the steel frame section of the school. Figure 5-3 shows damage to the Kelly Elementary School. Arrows show separation between the bond beam and its supporting wall and separation between the bond beam and roof bar joists. At both locations, connections between the bond beam, joists, and walls were adequate for gravity load, but could not carry the high uplift loads that were caused by winds associated with the violent tornado.

FIGURE 5-3: Kelly Elementary School, in Moore, Oklahoma, hit by vortex of violent tornado. Damage to school displaying separation between the bond beam and supporting wall and separation between bond beam and roof bar joists.

Figure 5-4 shows a close-up of a joist end over the old cafeteria. The arrow shows a location where the roof deck was supported for gravity load, but not welded for uplift. Below the arrow, broken welds can be seen. Also visible in Figure 5-4 is the lower portion of the external wall. As illustrated in the photograph, no effective vertical reinforcement was found in the wall. Consequently, the wall had low resistance to uplift in combination with high lateral wind loads.

FIGURE 5-4: Failed structure showing broken deck welds, and no effective vertical reinforcement. Kelly Elementary School, Moore, Oklahoma, hit by vortex of violent tornado.

5.1.3 Steel Frame with Masonry Infill Walls

The BPAT visited a regional outlet mall in Stroud, Oklahoma, where the entire roof was blown away and significant damage to the building was evident. This mall was struck by a moderate tornado that collapsed the central portion of the building's steel frame and damaged many of its masonry and steel frame walls. Figure 5-5 shows standing seam roof attachments of the decking to the purlins in one area of the mall that failed under the uplift loading. It was observed that threaded fasteners used to attach portions of the exterior cladding to the frame performed better than the standing seam roof attachments.

FIGURE 5-5: Metal roof deck of regional outlet mall, Stroud, Oklahoma, blown off when hit by moderate tornado vortex.

Figure 5-6 shows the attachment of columns to the foundation and attachment of the wall bottom plates to slab concrete. At the arrow on the right in Figure 5-6, anchor bolts were provided but the apparent lack of nuts on the anchor bolts permitted the column to lift off of the foundation. At the center arrow, anchor bolts with properly attached nuts provided a high level of restraint to column lift off. The arrow at the left of Figure 5-6 shows a wall bottom plate that was attached to the concrete slab by power driven nails. Although the plate held at this location, lack of penetration by the nails into the concrete permitted the plate to pull out at many other locations. Additional nail penetration would be needed to assure consistent attachment of wall bottom plates to the slab.

FIGURE 5-6: Attachment of columns to foundation and attachment of wall bottom plates to concrete slab. Regional outlet mall, Stroud, Oklahoma, hit by moderate tornado vortex.

Most bolts with nuts exhibited a ductile steel failure as shown in figure 5-7. This was the failure mode observed in most cases. This was also the failure mode for the anchorages at the steel water tower in Mulhall, Oklahoma. However, some of the bolts observed at the mall did pull out of the concrete foundation, indicating a failure in the concrete bond (see Figure 5-8).

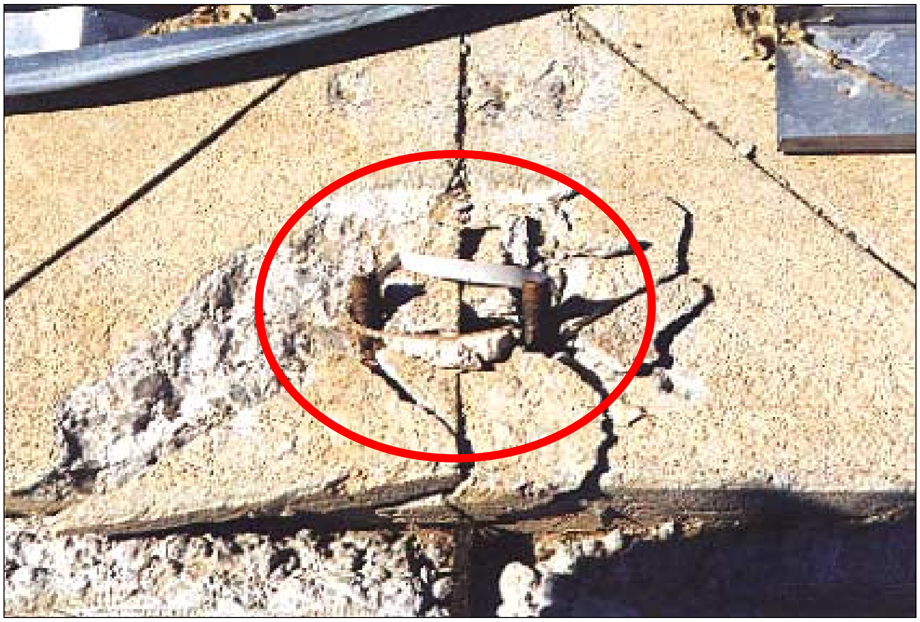


FIGURE 5-7: Column anchors that exhibited ductile failure at the regional outlet mall in Stroud, Oklahoma, hit by moderate tornado vortex.

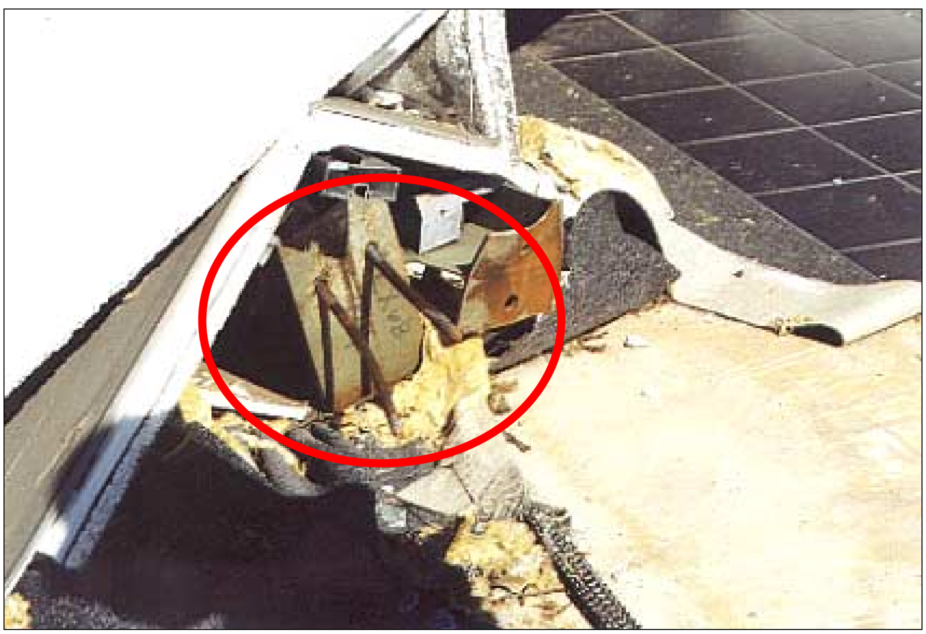


FIGURE 5-8: Column anchors that withdrew from concrete foundation at the regional outlet mall in Stroud, Oklahoma, hit by moderate tornado vortex.

5.1.4 Light Steel Frame Buildings

The BPAT investigated the regional outlet mall that was destroyed in Stroud, Oklahoma. Figure 5-9 shows damage to the outlet mall. In this structure, most of the metal roof deck was blown off by the tornado. In addition, much of the metal curtainwalls used above lower, exterior masonry walls were destroyed.

FIGURE 5-9: Stroud Regional Outlet Mall, Stroud, Oklahoma was struck by the vortex of a moderate tornado.

5.1.5 Laminated Wood Arches with Wood Frame Roof

Lack of load path also resulted in severe damage to the Regency Park Baptist Church in Moore, Oklahoma. This building was approximately one block north and across the street from Kelly Elementary School. The vortex of a violent tornado passed approximately a few hundred yards to the south. Figure 5-10 shows the rigid frames remaining after the roof had been removed by the tornado. Loss of load path between the rigid frames and the roofing resulted in severe damage to the facility.

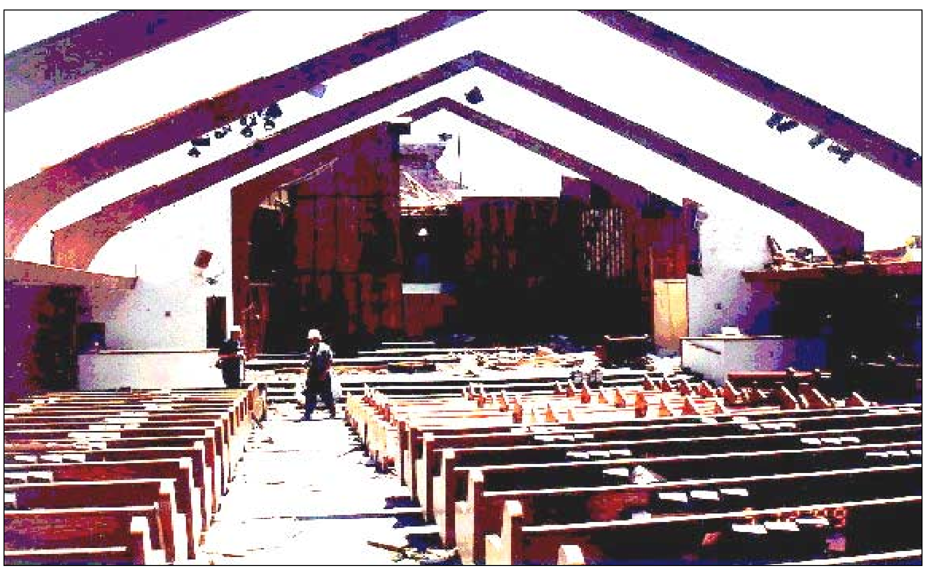


FIGURE 5-10: This church suffered loss of roof due to lack of load path between the rigid laminated wood arches and the roof purlins which supported roof sheathing. Inflow area of a violent tornado, Moore, Oklahoma.

5.1.6 Masonry Walls with Pre-cast Hollow Core Floors

In several locations, combined effects of upward suction wind loads with horizontal wind loads caused unexpected damage to structures. When a continuous load path for uplift and lateral loads did not exist, roof failures and upper level floor failures were observed. Figure 5-11 shows the remains of a motel in Mid West City, Oklahoma, hit by a violent tornado vortex. The arrows show a steel beam that had been deflected inward significantly when the floor slab was lifted during the tornado. There was no positive connection between the steel beam and the floor above.

FIGURE 5-11: Motel in Mid West City, Oklahoma that experienced major damage when struck by the vortex of a violent tornado.

5.2 INCREASED LOAD

At a plastics manufacturing plant in Haysville, Kansas, a combination of upward and horizontal wind loads when the plant site was hit by a violent tornado caused out-of-plane buckling of the bottom flange of a main girder supporting the roof (Figure 5-12). One arrow shows the column that supports the girder, while the other arrow shows the bottom flange of the girder. It can be seen that the bottom flange has displaced significantly sideways in relation to the top flange of the girder. Inspection along the length of the girder indicated that the bottom flange was braced along its length at every purlin except at the location of the supporting column. This lack of bracing permitted buckling and out-of-plane displacement of the bottom flange. However, due to the light gravity loads left on the roof after the wind forces diminished, collapse did not occur.

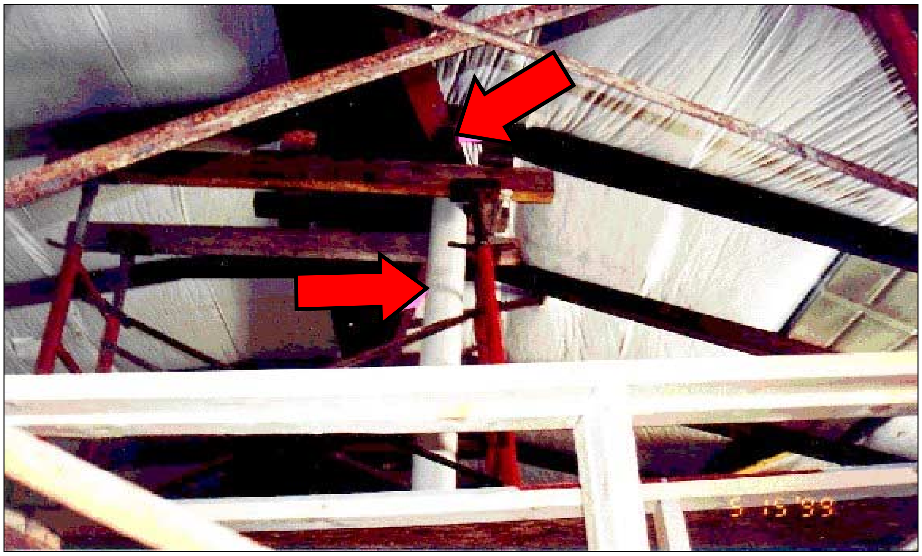


FIGURE 5-12: Out-of-plane buckling of the main girder supporting the roof created by a combination of uplift and horizontal wind loads. Plastics plant, Haysville, KS hit by violent tornado. This building was in the inflow area of a severe tornado.

Another example of the effects of uplift and horizontal wind forces is seen in Figure 5-13 at Kelly Elementary School in Moore, Oklahoma. The exterior wall collapsed inward indicating that the roof had lifted up as the wind loads acted inward on the wall. Failure to have a continuous load path from the joists supports into the masonry wall to resist uplift forces contributed to collapse of the wall. The exterior masonry wall is seen lying on the floor beneath the collapsed roof structure.

FIGURE 5-13: Collapsed roof structure and exterior at Kelly Elementary School in Moore, Oklahoma struck by the vortex of a violent tornado.

The Westmoore High School in Moore, Oklahoma, was a relatively new structure that was within 100 yards of the vortex of a violent tornado. Although most of the roofs stayed on this building, the roof over the auditorium stage was blown off. Figure 5-14 shows the walls where the bar joists had been attached prior to the tornado. In all cases, welds failed between bar joist ends and embedments in the walls in the auditorium stage roof. This loss of load path permitted the roof to be lifted up off of the reinforced concrete walls.

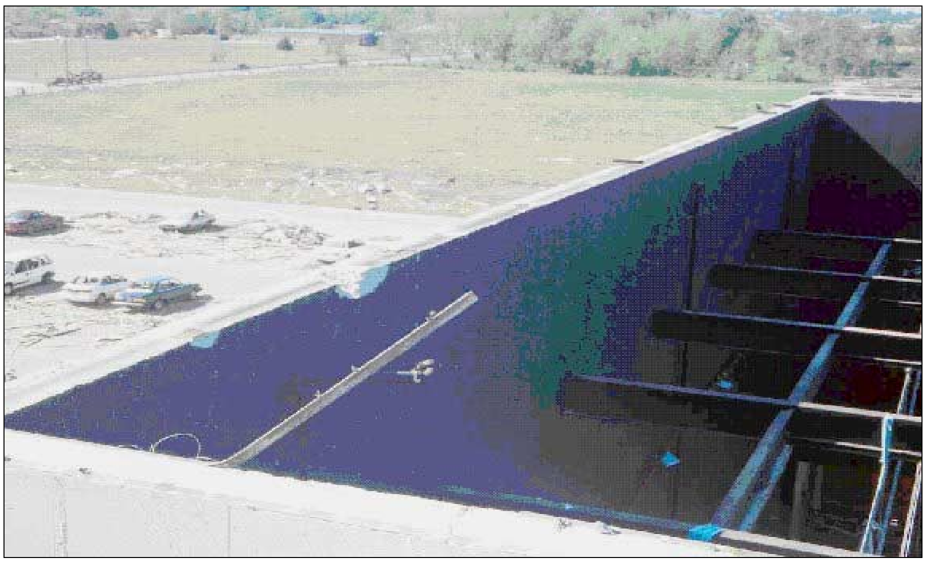


FIGURE 5-14: Roof blown off over top of auditorium at Westmoore High School, Moore, Oklahoma hit by inflow winds of violent tornado.

Figure 5-15 shows the exterior of the reinforced concrete wall at Westmoore High School following the tornado. This 12-in thick by approximately 35-ft-tall wall remained essentially undamaged, even though the diaphragm action of the roof was lost. The construction of the stage area integrated an I-beam horizontal frame, shown in Figure 5-14, with the reinforced concrete walls. This frame provided diaphragm action that helped stabilize the walls. Prior to the tornado, the bare concrete had been covered with a decorative metal curtainwall. The entire curtainwall blew off during the tornado while brick masonry veneer on the lower wall remained, with virtually no damage.

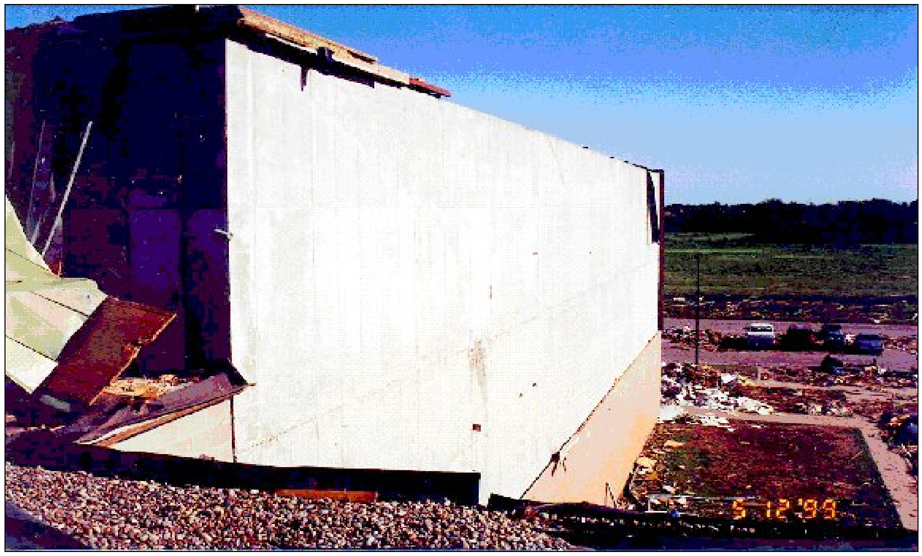


FIGURE 5-15: Exterior view of an undamaged reinforced concrete wall, Westmoore High School, Moore, Oklahoma, hit by inflow winds of a violent tornado. Note: decorative metal wall covering was peeled from this wall.

5.2.1 Tilt-up Precast Concrete Walls with Steel Joists

Diaphragm action is needed to supply lateral support at the tops of external walls for commercial buildings with open architecture, such as warehouses and open office buildings. When the support is lost, wind load resistance is greatly reduced and structural failure often follows.

Figure 5-16 shows a tilt-up concrete wall that failed after loss of an interior diaphragm made up of steel joists and metal deck. This building was located approximately 200 yards from a violent tornado vortex near Del City, Oklahoma. As can be seen in Figure 5-16, the wall was well attached at the foundation level. However, loss of diaphragm at the top of the wall permitted the wall to blow outward and collapse.

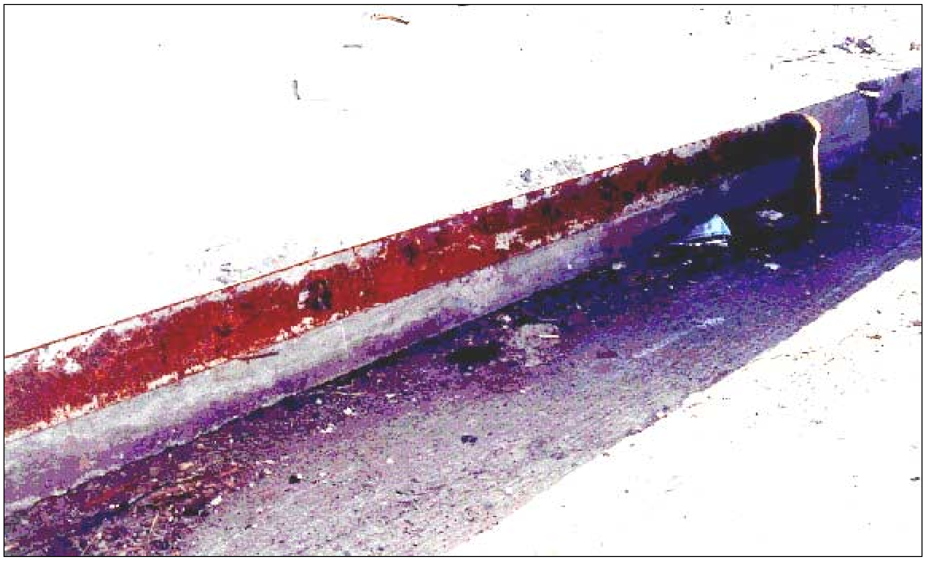
FIGURE 5-16: Failure of tilt-up concrete wall in Del City, Oklahoma, hit by inflow winds of a violent tornado.

A factor contributing to collapse of the tilt-up wall was the placement of the vertical reinforcement. Close inspection of the broken surface indicated that reinforcing bars were placed near the exterior face of the wall. In tilt-up construction, the bars commonly are placed at mid-thickness of the wall. Placement of the reinforcement, as indicated by the arrow in Figure 5-16, significantly reduced the resistance of the wall to outward deflection or movement.

Figures 5-17 and 5-18 show the top of the tilt-up precast concrete wall that failed. Figure 5-17 shows that diaphragm action provided by a beam supported by the wall was lost when the beam pulled out of the wall pocket. Failed welds tying the roof into the top of the tilt-up wall can also be seen in Figure 5-18. Visual inspection showed that only one of the four walls of the building collapsed. The other walls had part of the diaphragm action provided by remaining portions of the roof.

FIGURE 5-17: Top of failed tilt-up wall.

FIGURE 5-18: Top of failed tilt-up wall.



Tilt-up walls at a facility that was located under the vortex of a moderate tornado in Wichita, Kansas, survived virtually undamaged, despite loss of metal deck roofing. As can be seen in Figure 5-19, trusses spanning the open area maintained diaphragm action.

FIGURE 5-19: The tilt-up precast concrete walls in this building did not fail when the roof system failed. Note: many roof joists are still in place. Building was located in Wichita, KS and was hit by moderate tornado vortex.

5.2.2 Load Bearing Masonry with Steel Joists

In Figure 5-19, damage to a portion of the building having a steel joist roof supported on masonry walls can be seen at the left. Walls in this portion of the building collapsed when subjected to the vortex winds of a moderate tornado. Even though some diaphragm action was maintained, the masonry walls did not have enough lateral load resistance under the combined uplift and horizontal load of the tornado.

Figure 5-20 shows damage to both interior and exterior unreinforced masonry walls (URM) at Kelly Elementary in Moore, Oklahoma. Wind loads due to the vortex of a violent tornado lifted the roof system until the bond beam atop the URM wall failed. When this bond beam failed, the roof separated from the building and some interior walls failed.

Figure 5-20: Damage to interior and exterior unreinforced masonry walls when bond beam failed at Kelly Elementary School in Moore, Oklahoma. The school was struck by the vortex of a violent tornado.

5.2.3 Masonry Walls with Pre-cast Hollow Core Floors

At a motel in Mid West City, Oklahoma, which was hit directly the vortex of a moderate tornado, failures occurred between the second floor precast hollow core panels and their supporting walls.

Figure 5-21 shows the location where hollow core plank had formed the second floor. The arrow at the right shows a dowel from the masonry wall into grout between the ends of two hollow core panels. One of the panels that had been at the edge of the building was found up on the second level and across on the far side of the building as shown by the arrow on the left of Figure 5-21. Apparently the uplift wind forces from the tornado were large enough to overcome the tie-down force provided by the very short dowels. The hollow core plank appears to have been lifted and blown across the width of the building.

FIGURE 5-21: Hollow-core plank formed on second floor of a Midwest City, Oklahoma, hotel that was struck by the vortex of a moderate tornado.

Elsewhere along the edge of the second floor of the motel, failure occurred between the hollow core planks and exterior walls of the building. As shown in Figure 5-22, lower plates for the walls had been attached to the hollow core planks using power driven anchors. As indicated by the arrows, the powder driven anchors pulled out during the tornado.

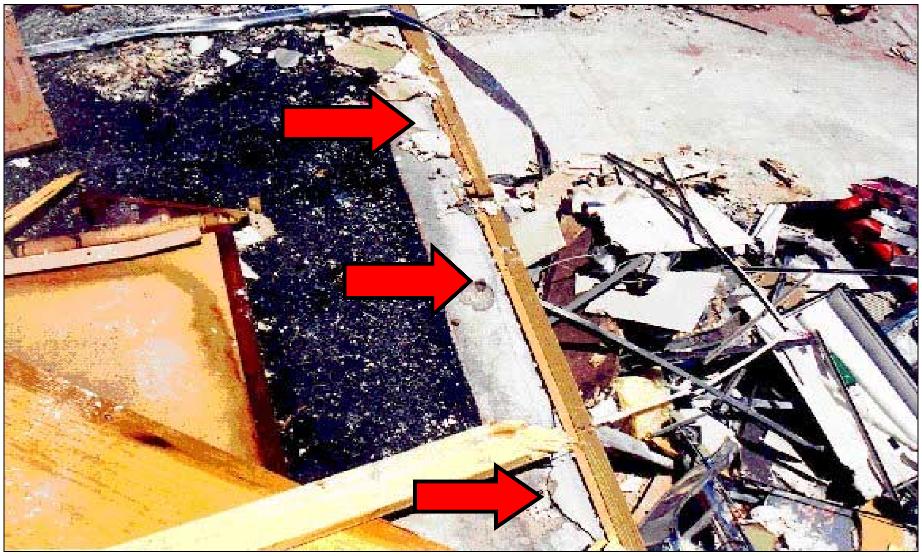


FIGURE 5-22: Attachments of lower plates for wall to hollow core plank using power driven anchors failed when required to carry loads generated by the winds of a moderate tornado vortex. This motel was located in Midwest City, Oklahoma.

5.3 NON-RESIDENTIAL BUILDING ENVELOPES

In many cases, tornado damage patterns observed demonstrated that additional collapse of buildings was caused by breach of the building envelope. Openings in the envelope caused by loss of garage doors or broken windows frequently contributed to local loss of roofs or walls of the building. The following is based on a limited number of non-residential building site visits by the BPAT.

5.3.1 Roof Coverings

The following roof types were observed:

- Ethylene propylene diene monomer (EPDM) with aggregate (stone) ballast
- built-up (aggregate ballast over cap sheet)
- metal panel (architectural and structural) including standing seam
- tile

All of the roofs observed experienced blow-off problems, except for a built-up cap sheet roof that was at the periphery of the tornado damage area. Windborne missiles, wind driven and free-falling, punctured some of the roofs. In the case of metal panels on pre-engineered frames, it was not determined whether the panels blew off before or after failure of the supporting frames.

Site visits revealed poor connections between wood nailers and the structure at roof perimeters. In one case, roofing nails were used to attach perlite insulation. This type of attachment offered very little uplift resistance.

In one case, loss of a large portion of a built-up roof with aggregate ballast resulted in significant rainfall water infiltration into a hospital in Stroud, Oklahoma. After the storm, the hospital was closed and the patients moved to a facility about 30 miles away, which significantly reduced the availability of emergency medical services over this area of rural Oklahoma. The characteristics of the damage to the hospital were not indicative of tornado winds due to its distance from the tornado vortex. Rather, it is likely that the damage was caused by thunderstorm winds. The failure initiated when the coping lifted or with lifting of the nailer the to which the coping was attached (Figure 5-22). The nailer was poorly attached to a 4-in CMU that formed the parapet wall. In some areas, the CMU block parapet lifted slightly.

Figure 5.23: Nailer at the roof of the hospital in Stroud, Oklahoma. The roof surface in this photo was replaced prior to this photo, but the same nailer was used again.

5.3.2 Wall Coverings

Brick veneer is discussed in Section 4.1.3.2. Some metal wall coverings over steel studs collapsed (Figure 5-24). Some Exterior Insulating Finishing System (EIFS) failures were observed.

FIGURE 5-24: This metal-clad wall covering collapsed and in other areas it was blown completely away.

5.3.3 Laminated Glass

In a few instances, examples of laminated glass performance were observed. In some cases the glass remained in the frame after windborne missile impact (Figure 5-25). In another case, the glass was punched out of its frame. The school in Figure 5-25 is located adjacent to Regency Park Baptist Church in Moore, OKLAHOMA in Figure 5-10. The vortex of a violent tornado passed a few hundred yards south of this building.

FIGURE 5-25: The corner of a table penetrated this laminated glass, but the glass remained in its frame. This school suffered major damage from inflow winds of a violent tornado in Moore, Oklahoma.

5.3.4 Garage Doors, Exterior Doors and Windows

The breach of overhead commercial doors caused internal pressurization of the structure leading to significant load increases. Not unlike the residential case, a breach in the building envelope was observed, in some cases, to initiate a partial or total failure of primary structural systems. This was particularly true for pre-engineered buildings, which typically had little redundancy in load transfer of their structural systems. Figure 5-26 shows a breached commercial overhead door belonging to a bread manufacturing and distribution center in Wichita, KS. The building exterior walls were constructed using both concrete masonry block and tilt-up concrete panels. The roof deck was standing seam metal on a Z purlin system. The door failure appears to be a result of positive (inward) pressure. The breach may have caused a sufficient enough rapid increase in load to produce failure of the URM block wall. It is worth noting the location of the failed door is near a corner where high negative suction or (outward) pressure is likely to occur on the adjacent wall. As a result of the exterior wall collapse, severe damage to the roof system occurred due to the loss of the load bearing exterior support wall. However, notice that the roof collapsed to the interior of the building, which may indicate that uplift loads acting on the roof were insufficient to cause progressive peeling failure of the roof system.

FIGURE 5-26: Failure of roof and walls on structure due to increased loads caused by initial failure of garage door, Wichita, Kansas.

Figure 5-27 illustrates another condition in Wichita, KS where breach of the building envelope contributed to additional structural damage. In this case, loss of showroom windows and an overhead door greatly increased loads in the showroom and on the wall at the left of the photograph. These increased loads caused the walls to fail and the roof to partially collapse, thereby greatly increasing structural damage in the building.

FIGURE 5-27: Additional structural damage caused by breach of envelope in Wichita, Kansas.

Figure 5-28 shows a steel door that appears to have been opened by impact of a heavy object. This door at Kelly Elementary School in Moore, Oklahoma, led into an area where the roof was completely missing. The breached door may have caused an increase in load that propagated damage to that part of the building envelope. A nearby door, which was also heavily impacted, but did not open, was located in an area of the school that saw less damage to the wall and roof of the building.

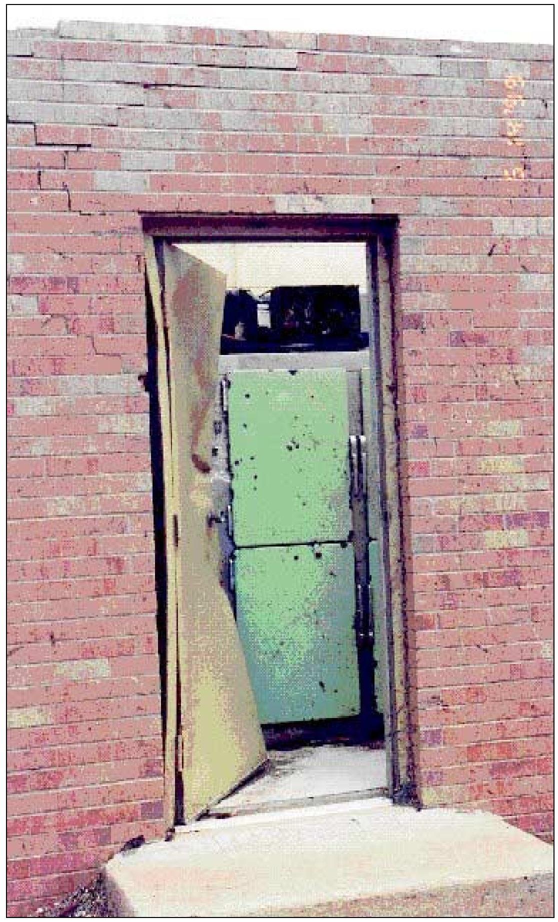


FIGURE 5-28: Damaged door most likely opened by impact with heavy object. Kelly Elementary School, Moore, Oklahoma.